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TITLE

RAPID PROTOTYPING AND THE HUMAN FACTORS ENGINEERING PROCESS

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Rapid prototyping and the human factors engineering process

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Rapid prototyping or 'virtual prototyping' of human–machine interfaces offers the possibility of putting the human operator 'in the loop' without the effort and cost associated with conventional man-in-the-loop simulation. Advocates suggest that rapid prototyping is compatible with conventional systems development techniques. It is not clear, however, exactly how rapid prototyping could be used in relation to conventional human factors engineering analyses. Therefore, an investigation of the use of the VAPS virtual prototyping system was carried out in five organizations. The results show that a variety of task analysis approaches can be used to initiate rapid prototyping. Overall, it appears that rapid prototyping facilitates an iterative approach to the development of the human–machine interface, and that is most applicable to the early stages of systems development, rather than to detailed design.

Keywords: Rapid prototyping, virtual prototyping systems development, task analysis

Introduction

The human factors engineering (HFE) process recommended for the development of human–machine systems is based on a series of increasingly detailed analyses of operator functions and tasks[1,2]. One conclusion from a review of the application of human factors engineering in 10 large projects was that more use should be made of man-in-the loop simulation to supplement those analyses, but that such simulation is expensive and time consuming, precluding widespread use[3]. Rapid prototyping is one promising technology which places the operator 'in the loop' without requiring the technical complexity of conventional man-in-the-loop simulation.

Rapid prototyping involves the construction and use of an executable model of a human–machine interface for system development, without the necessity for simulating the complexity of the actual system. The majority of rapid prototyping systems are intended for the development of human–computer interfaces. These systems support the representation of CRT-based displays such as menus and data structures (see Keyson and Parsons[4], for example). A limited number of rapid prototyping systems permit the representation of conventional human–machine interfaces consisting of dials, knobs, switches, etc using high-resolution colour CRT displays[5]. These systems are sometimes called 'virtual prototypes' to distinguish them from the more application-specific rapid prototyping systems. Virtual prototyping systems allow the designer to represent interfaces such as the dashboard of a car, a keyboard or the control panel of a ship's radar. Users can interact with convincing representations of the displays and controls using a cursor on the CRT screen, or using touch-sensitive overlays. For example, representations of keys can be activated, switches can be moved from one position to another, or continuous rotary controls can be moved through an arc. In this respect these 2-dimensional prototypes can be considered to be 'dynamic', or 'functioning' mock-ups[2].

Typically, mock-ups are scheduled late in the preliminary design phase of large systems[2,3], because the detailed task analyses required to specify the human–machine interface are not available earlier (Figure 1). It is not clear, however, that rapid prototyping could be used, or is being used, in the same way as a mock-up. Williges and Hartson[6] recommended that rapid prototyping be used in an iterative approach to design development, following initial design. Boehm *et al*[7] recommended that for most large projects, and for many smaller ones, a mixture of rapid prototyping and specifying be used, rather than exclusive use of either one. Andriole[8] recommended that prototyping be initiated early, to refine preliminary user requirements. Dearnley and Mayhew[9] suggested that prototyping will be compatible with any of the methodologies used in the system development cycle.

These recommendations suggest that rapid, or virtual,

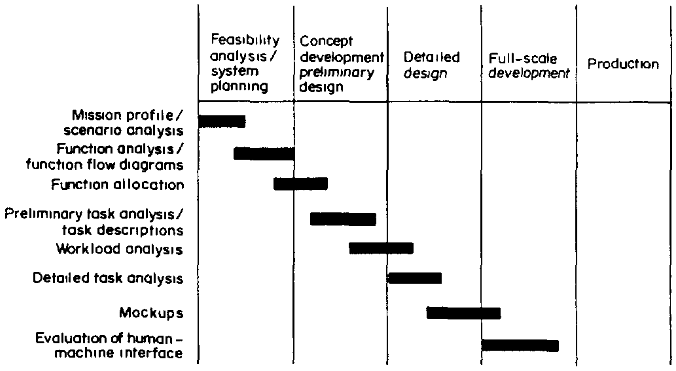

Figure 1 Typical schedule of human factors engineering activities in a large system development project

prototyping could be used throughout the design/ development process. In general, it could be expected to be useful for concept development, preliminary design, detailed design, procedures development, and test and evaluation. Its application could be expected to encourage an iterative approach to design, and an iterative approach to design should emphasize the importance of performance measurement. Given the obvious link with human factors engineering, it could be expected that rapid, or virtual, prototyping would be used by HFE specialists. Rapid prototyping could be expected to require some task analysis input but to reduce the need for detailed task analyses. But it is not clear how rapid prototyping would be linked to operator task analysis in the development of complex systems, if detailed task analyses are not available until late in the preliminary design phase.

To investigate these expectancies and the question about the relationship between rapid prototyping and task analysis, an investigation was conducted on the use of a specific prototyping system, the VAPS® Virtual Applications Prototyping System*. VAPS is a software tool that runs on Silicon Graphics Inc IRIS® computer systems. VAPS uses object-oriented programming to provide the capability to model and manipulate convincing graphic representations of the displays and controls of the human–machine interface on a high-resolution, colour CRT.

Method

To conduct the survey, a sample of six industrial and government organizations using VAPS (version 0.6R2**), representing a wide range of applications, was contacted and asked to assist. Five organizations agreed to participate. Their applications of VAPS involved the representation of operator work-stations or consoles based on multi-function displays and controls such as a submarine command and control system, or specific operator displays and controls such as a heads-up display. The areas of application within the five participating organizations included three aircraft systems, two submarine systems, and one command and control system.

The investigation was conducted using a questionnaire followed by interviews with the respondents. The questionnaire covered the general design process (nine questions on user experience, applications, development life cycle and design procedures), the development of the human-machine interface (12 questions on by whom and how the interface design is developed), the derivation of operator performance requirements (two questions), the generation of ideas (four questions how the design features were derived), and use of the VAPS system (20 questions on by whom, how, and when the prototyping facility was used). The majority of questions required an open-ended answer. Examples of such questions are: 'How do you identify operator roles, functions and tasks related to the system being developed?' 'At what stage of the design process do you conceive the user interface?' One question required the respondents to rate the prototyping system on a scale of 1 to 7 for its effectiveness in various project applications such as conceptual development, system effectiveness, detailed design, etc (see Table 1).

Table 1 Survey questionnaire's rating question

Is VAPS less effective for some of the above activities than for others? Use rating scale on right side of the page and circle only one number on each scale using your best judgment.

Conceptual development	ineffective	1	2	3	4	5	6	7	effective
Feasibility studies	ineffective	1	2	3	4	5	6	7	effective
Planning a design	ineffective	1	2	3	4	5	6	7	effective
Detailed design	ineffective	1	2	3	4	5	6	7	effective
Operational procedures development	ineffective	1	2	3	4	5	6	7	effective
System effectiveness studies	ineffective	1	2	3	4	5	6	7	effective
Usability evaluation	ineffective	1	2	3	4	5	6	7	effective
User familiarization	ineffective	1	2	3	4	5	6	7	effective
Training	ineffective	1	2	3	4	5	6	7	effective
Other ____________	ineffective	1	2	3	4	5	6	7	effective
Other____________	ineffective	1	2	3	4	5	6	7	effective

* The study was conducted by Virtual Prototypes Inc of Montreal under contract No 03SE.W7711-8-7049 for the Defence and Civil Institute of Environmental Medicine, Toronto

** Since the start of this investigation a more recent version of the software, VAPS 1 0, has been released by the developer

Telephone discussions with a number of VAPS users within the five participating organizations showed them to have quite diverse backgrounds: two systems engineers, two human factors engineers/psychologists, two engineers, one computer scientist, one computer programmer, one designer and two technicians. Their experience in systems development differed widely, from six months to 14 years (median 2 years), on from one to 20 projects (median of four). One questionnaire was sent to each user organization and the respondents were encouraged to share the questionnaire among representative users. Six copies of the questionnaire were returned, representing the views of 11 people who had used VAPS in six development projects in the five organizations. One respondent felt unqualified to respond to all the questions, so the questionnaire data were incomplete. On-site follow-up interviews were conducted with the respondents to review and expand on the questionnaire replies. The answers to the interviews were summarized and compared[10]. Applications of the virtual prototyping system were ranked according to frequency of use in the six projects (Figure 2). Median ratings of the effectiveness of the prototyping system were calculated for those same six applications, based on ratings from the six questionnaires (Figure 3).

Results

As shown in Figure 2, most of the applications of the virtual prototyping system were in the areas of 'conceputal development', and 'usability evaluation'. Comparatively little use was made of the prototypes for 'feasibility studies' or for 'systems effectiveness studies'. Benefits reported from using the prototyping system included the ability to work on the human–machine interface well in advance of actual equipment being available, the ability to investigate the dynamic aspects of the interface, iteration of the interface design, and improved definition of requirements including the ability to confirm customer/operator agreement on the proposed design. One user group reported that they were moving away from mock-up testing as a result of employing the prototyping system.

In each of the six projects, the approach to developing design goals was based firmly on the company's interpretation of customer requirements. The approaches varied from brain-storming followed by the development of requirements by ex-operators of previous systems using 'seat of the pants' criteria, to formal, documented procedures. The latter included the complete cycle of requirements analysis, function/object oriented decomposition, preliminary design, detailed design, integration and test (see Meister[2]). Respondents reported that they did not employ formal system specification techniques such as CORE[11], SADT/IDEF®[12], Jackson or Yourdon techniques[13]. In one case, the prototype users had attempted to use one such technique, but found that the lack of supporting tools limited its usefulness.

The majority of respondents used some form of analysis to define operator roles, functions and tasks. The techniques included function flow analyses and input–output analyses[14]. In one case, manuals from existing systems were used. Four of the projects used a specific task analysis technique: two used operational sequence diagrams[14] supplemented in one case by detailed analyses of control and display modes; one used a sequence of display 'frames' similar to a storyboard approach; one used augmented transition networks (ATN). Critical tasks were identified by a variety of approaches, from analysis and experimentation to expert opinion. Apart from these task analyses, there was no formal attempt to define or model the operator tasks or the human–machine interface.

The VAPS users reported that the human–machine interface concept was developed early in the systems design/development process. In four of the six projects the interface had been defined by other (human factors engineering) specialists and the prototype had been developed from that previous work. Users reported that interface designs were often evolutionary from one system to another. Some features, such as information presentation, screen design or display and control functions and protocols were carried over from one project to the next. This occurred even though the applications could differ widely – for example, from a high-performance jet to a transport aircraft.

The majority of respondents reported that ease of use and operator performance were critical considerations in the development of the human–machine interface. In only two of the six projects, however, did the prototype users refer to published human engineering

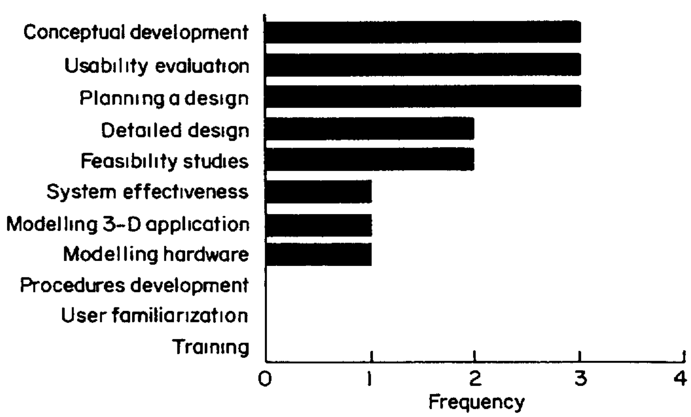

Figure 2 Uses of a virtual prototype system in six projects

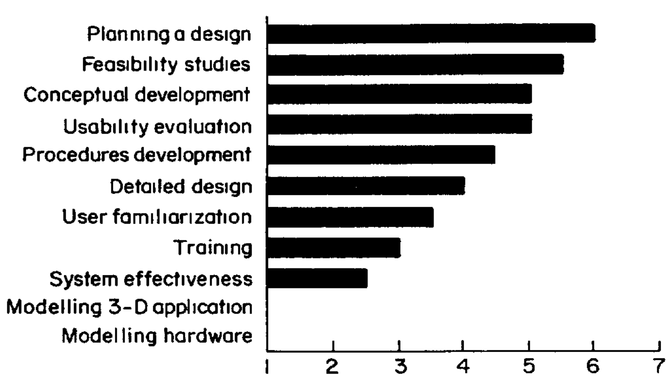

Figure 3 Medium ratings of six virtual prototype applications (scale of 1–7)

design guidelines. Those references were US MIL-STD 1472C and the Guidelines to Human-Computer Interface Design[15]. A third project used very general 'principles' for the development of an aircraft crew-station from a book on aviation human factors. Respondents reported using a variety of criteria which they thought contributed to ease of use of the human–machine interface. These criteria ranged from the need for the interface to be 'intuitive' to requirements for interpretability, consistency, legibility and minimum number of operator actions.

As shown in Figure 3, the VAPS prototyping system received varying ratings for its degree of effectiveness for facilitating different system design/development activities. Virtual prototyping was rated as quite effective for early design/development activities, and for usability evaluation, and less effective for activities which take place later in the development process. The respondents reported that rapid prototyping did make the process of developing the human–machine interface more iterative, and in five of the six projects they had conducted some form of evaluation of their prototypes. There was little formal experimentation or test, however. For the most part, the evaluations were demonstration/validation exercises in which other designers, potential operators or ex-operators of previous systems were shown the prototypes and asked for comment. The speed of response of the prototypes to operator input proved to be a critical factor limiting some of the evaluations. Two prototype users found the response speed too limited for a full-scale test and evaluation of their particular system†. Consequently, respondents reported that the rapid prototype was more suitable for evaluation than for test.

Discussion

Overall, the VAPS users described a situation similar to that found in a previous review of human factors engineering applications in development projects such as aircraft and ship systems[3]. The approach taken to systems design and development differs widely between organizations, and a very limited range of HFE techniques is used in any one organization. Expectancies about the applicability of rapid prototyping throughout the development cycle were partially confirmed by the investigation. The VAPS system had been used for conceptual development, planning a design, detailed design, procedures development, usability evaluation and customer/operator familiarisation. That none of the projects surveyed employed the virtual prototyping system fully for every phase of system design/development suggests that the tools are under-exploited.

The most frequent applications were for conceptual development and usability evaluation (Figure 2), and the prototyping tool was rated most highly for planning a design, feasibility studies and conceptual development (Figure 3). These activities take place early in the design/development process. This is encouraging, because it shows that prototyping can address human factors engineering in the concept development stage, rather than being delayed until the design stage of systems development. The frequency of use of the prototyping tools for usability evaluation and the relatively high effectiveness rating for that application are supported by user reports of improved ability to confirm customer/operator agreement on the proposed design. This is consistent with the experience of other users of rapid prototyping[16].

Although the virtual prototyping system did facilitate design iteration, the approach to evaluation of the prototypes was quite limited. Given the lack of use of formal 'usability' design criteria in the development of the prototypes, it might have been expected that test and evaluation would be quite important to the prototype users. The general lack of use of systems effectiveness criteria, and strong emphasis on subjective measures for evaluation, is not unusual however: the reports are consistent with the findings from a much more extensive survey of test and evaluation practice[17]. Reports of difficulties in using the rapid prototype for systems effectiveness studies reflect Meister's findings that appropriate performance measures are difficult to develop. The reports also reflect the limitations of the prototyping system, which had no built-in facility for collecting operator performance data, and which had a slow response speed for some applications. The low ratings for 'user familiarization' and for 'training' applications are thought to reflect constraints on prototype operating procedures imposed by those limitations. Therefore, the potential of rapid prototyping as a low-cost alternative to man-in-the-loop simulation requires more investigation.

The prototyping tool received relatively low ratings for detailed design and for user familiarization and training, all of which take place later in the design development process. The low ratings for detailed design are unexpected. They may reflect the compromises to scale and level of detail that are necessary in order to represent a complex human–machine interface on one CRT screen. Respondents seemed to expect more capability for detailed design from the system. One respondent thought that users should be able to produce engineering drawings of the proposed system directly from the prototyping system (VAPS permits the software developed for the prototype to be ported directly to an application model[18], as well as providing print-outs of each display page). This suggests that potential users of virtual prototyping systems should be aware of the limitations imposed on detailed design by the technology. Despite the relatively low ratings for training (Figure 3), it is believed that a virtual prototyping system could serve as a powerful low-cost training medium. In fact there is little difference between the technology used to develop virtual prototypes and that used for touch-screen interactive Computer Aided Learning (CAL).

In most cases, the users of the VAPS were not the human factors specialists who developed the human–machine interface concept. It appears that, as with

† Virtual Prototypes Inc claim that any problems with speed of response have been solved with the more recent software issue

many new technologies, rapid or virtual prototyping is seen as requiring specialist users. Given that only three of the prototype users had a human factors background, it is disturbing that human factors engineering design standards were used in only two of the six projects. This suggests that HFE design standards should be incorporated into rapid or virtual prototyping systems.

The limited use made of formal requirements definition techniques, and the limited use of task analysis techniques, are consistent with the findings from a previous survey of HFE applications[3]. Formal human factors engineering analyses are labour intensive, and reports from analysts confirm that the effort required discourages iteration. The majority of task analyses are conducted at a 'gross' level rather than at a detailed task level. The variety of approaches to task analysis taken by the VAPS users suggests that the prototyping technology does not constrain the approach to task analysis or to design development. More importantly, the investigation showed that task analyses can be available early enough to make a contribution to concept development. This is because the 'top-down' deductive approach to human factors engineering advocated in many texts[2,14] is not routinely applied in practice. The steady evolution of designs from one project to the next reported by the respondents reflects the engineer's 'obsession with hardware'[2]: it means that design and development is a mixture of 'top-down' and 'bottom-up' approaches, as others have shown[19,20]. Given this, rapid prototyping appears to be an effective complement to task analysis, particularly since it does seem to encourage iteration of the design.

Overall, the investigation suggests that rapid, or virtual, prototyping is still in the developmental stage, and that neither the prototyping tool, nor the process which exploits it, have reached maturity. From the investigation it is possible to identify two areas in which rapid prototyping systems, as exemplified by VAPS, could be augmented. The first area is the incorporation of human factors engineering design standards into the prototyping system. The second area is the development of the means to collect operator performance data for evaluation of the prototype. The variety of approaches taken by the prototype users requires that such augmentations do not constrain the design and development process, as others have noted[21,22].

Conclusion

Based on a limited survey of users of the VAPS Virtual Prototype system, it is concluded that rapid, or virtual, prototyping is an effective technology which complements human factors engineering analyses in the development of human–machine interfaces. The investigation showed that approaches to systems design and development and the applications of such prototyping vary widely among users. Overall, rapid or virtual prototyping appears to be most useful in the early stages of design, for concept development and feasibility studies. This is encouraging, because it implies that prototyping can be used as a vehicle for moving forward the point of application of human factors engineering activities from the detailed design stage to concept development.

The investigation also confirmed that rapid or virtual prototyping encourages design iteration. Test and evaluation, which is a necessary part of such iteration, requires fast response times from the prototyping tool, as well as the facility to measure operator performance. The potential of rapid or virtual prototyping to serve as a low-cost alternative to man-in-the-loop simulation requires more investigation. Potential users should be aware that virtual prototyping of complex conventional human–machine interfaces could involve compromises of scale and detail.

Rapid or virtual prototyping is not necessarily used by human factors engineering specialists or by those conducting the human factors engineering analysis for a project. Thus any such prototyping system must permit flexibility in use, and should facilitate the integration of human factors engineering design standards and task analysis information.

The investigation confirmed that there is a direct link between task analysis and rapid or virtual prototyping, and that the task analyses needed to produce the prototype can be available early enough in complex development projects to be applied during concept development.

Potentially useful developments of rapid or virtual prototyping systems include the incorporation of human factors engineering design standards into the prototyping systems, and the development of a performance measuring capability. Such developments should permit users as much flexibility as possible in their approaches to prototyping.

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